Efficiency of GaN/InGaN light-emitting diodes with interdigitated mesa geometry

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GaN/InGaN light-emitting diodes (LEDs) with different mesa structures are studied. The optical emission power as well as current–voltage characteristics of different mesa patterns are measured. The results show that the optical emission of the device with interdigitated patterns is higher than devices with traditional square-shaped patterns. The leakage current is found to increase as the mesa sidewall perimeter increases. Based on the analysis, it is concluded that a surface leakage current flows across the mesa sidewall and the leakage current is directly proportional to the mesa perimeter. The implications of the results for large-area scalable LED structures are discussed. © *2001 American Institute of Physics.* [DOI: 10.1063/1.1405145]

Ever since Nathan *et al.* reported the first practical light-emitting diode (LED) in 1962,[1] LED performance has been greatly advanced by improved materials growth, materials systems,[2] structures,[3,4] and better contacts.[5] In this letter, we report an efficiency improvement in GaN/InGaN LEDs by employing interdigitated mesa patterns, which are different from traditional square-shaped mesa patterns. The effect of interdigitated mesa patterns with different geometric parameters on current–voltage ($I-V$) characteristics and optical power are studied. The results are analyzed based on the geometric parameters of the LEDs. The study reveals that interdigitated mesa patterns generally improve the optical power due to a more uniform current distribution[6] and increased light extraction area. The analysis shows that they are scalable and can be used in high-power, large-area devices.[7] Finally, the study reveals that the leakage current increases with the mesa sidewall perimeter. The likely reason is a surface leakage current flowing across the mesa sidewall.[8]

The epitaxial layers of the LED wafer were grown by organometallic vapor-phase epitaxy on sapphire substrates. The epitaxial layers consist of a 2-μm-thick highly conductive n-type lower cladding layer, a GaN/InGaN multiple-quantum-well active region with ten wells, and a 0.3-μm-thick p-type GaN upper cladding layer. Different mesa geometries including two square-shaped structures and three different interdigitated structures were investigated. Square-shaped and interdigitated mesas were formed by inductively coupled plasma etching using Cl_2. The etching depth was 1.2 μm. Titanium metalization (500 Å), annealed at 800 °C for 30 s in a N_2 ambient was used as the n-type contact. Ni metallization (500 Å), annealed at 400 °C for 300 s in a N_2 ambient was used as the p-type contact. A micrograph of the LED structures is shown in Fig. 1. The dimensions of the square-shaped and interdigitated LED structures are given in Table I.

Compared to the square-shaped mesa structures, interdigitated structures generally have a larger mesa perimeter. The $I-V$ characteristics of different mesa structures are shown in Fig. 2. It reveals that the leakage current for both forward and reverse bias increases as the mesa perimeter increases. Due to the fact that all the samples are fabricated side by side on the same wafer, the material properties are the same for all devices. Thus, the leakage current due to threading dislocations or In composition fluctuation[9] is the same for all LEDs. It is also known that the dry-etching process for pattern transfer can lead to surface and sidewall damage.[10,11] The likely explanation for why the leakage current increases with the mesa perimeter is that the current bypasses the active region by flowing from the p-type contact over the mesa sidewall[11] to the n-type contact.

The emission spectrum of the devices peaks at 460 nm with a full width at half maximum of 30 nm. The optical emission power of different patterns is measured from both the backside and the frontside of the device. The optical emission power measured from the backside and frontside is shown in Figs. 3(a) and 3(b), respectively, as a function of

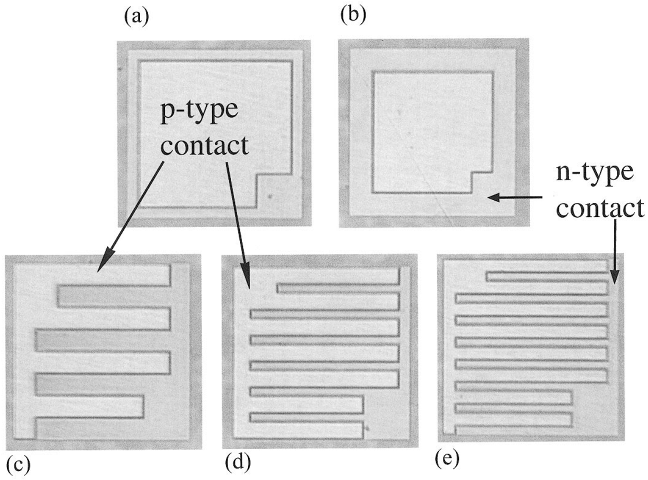

FIG. 1. Micrograph of InGaN/GaN LEDs with (a) large square-shaped pattern; (b) small square-shaped pattern; (c) large finger interdigitated pattern; (d) medium finger interdigitated pattern; and (e) small finger interdigitated pattern.

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TABLE I. Mesa area, mesa perimeter, contact area, and contact width of the different LED structures used in this study. The die size of all LEDs is 400 μm×400 μm.

	Mesa area (μm^2)	Mesa perimeter (μm)	*P*-contact area (μm^2)	*N*-contact width (μm)	*P*-contact width (μm)
Large square	116 100	1400	109 200	NA	NA
Small square	81 600	1160	75 900	NA	NA
Large interdigitated	80 500	3120	65 000	60	40
Medium interdigitated	104 600	5130	79 050	10	30
Small interdigitated	91 200	5920	61 900	10	20

injected current. They both show that the optical emission power is higher for the interdigitated patterns. Comparing the optical power of the two square-shaped patterns with different *p*-type mesa areas, the optical power is greater for devices with a larger *p*-type mesa area than devices with a smaller *p*-type mesa area. It implies that there are multiple factors playing roles in the device efficiency. Comparing interdigitated patterns with square-shaped patterns, the following effects are relevant in the efficiency change of the devices.

Efficiency increase in interdigitated structures due to:

(1) larger mesa sidewall area for better light extraction;
(2) more uniform current distribution across the *pn* junction;
(3) less light absorption of laterally waveguided modes due to a smaller contact area.

Efficiency decrease in interdigitated structures due to:

(1) smaller emission area as compared to the large square-shaped pattern (see Table I);
(2) higher leakage current passing across the mesa sidewall due to a longer mesa perimeter.

Figure 3 reveals that factors increasing the efficiency dominate in interdigitated devices. Comparing the optical power shown in Figs. 3(a) and 3(b), the optical power measured from the backside is higher than the optical power measured from the frontside due to the opaque metal contacts. Comparing the optical power of the interdigitated patterns with different finger sizes, the optical power increases when the interdigitated finger width gets smaller. As shown in Table I, without losing much emission area, the *p*-contact-area-to-mesa-area ratio decreases and the mesa sidewall area increases as the contact fingers width decreases. A smaller finger width also results in a more uniform current distribution.[6] Keeping the width of the *n*-type contact finger smaller than the size of the *p*-type contact ensures that the light-emitting mesa areas comprise the majority of the die area. So, decreasing the finger size will increase the mesa perimeter, i.e., increase the sidewall light extraction area and decrease the *p*-type-contact-area-to-emission-area ratio. This contributes to less contact absorption and more emitting area. Dimensions for contact fingers in interdigitated patterns are shown in Table I. The following formula is used to calculate the transfer length:

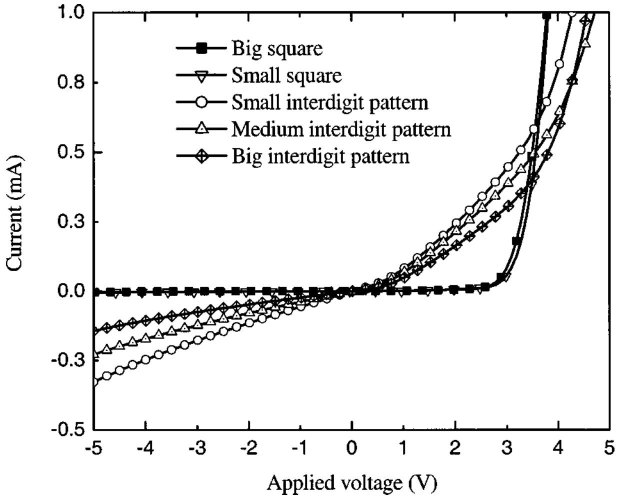

FIG. 2. Current–voltage ($I-V$) characteristics of GaN/InGaN LEDs with different mesa patterns.

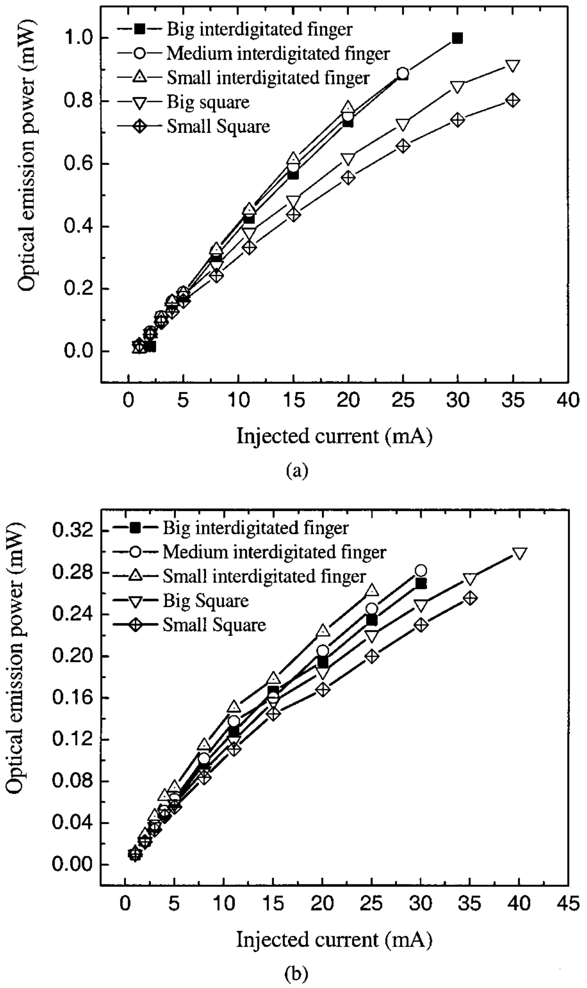

FIG. 3. Optical emission power measured from (a) the backside (substrate side) of the device and (b) the frontside (epi side) of the device.

$$L_T = \frac{\rho_c}{R_c w}, \tag{1}$$

where ρ_c is the specific contact resistance, R_c is the contact resistance, and w is the width of the contact. For n-type GaN, the typical specific contact resistance with an annealed Ti contact is $10^{-5}\,\Omega\,\mathrm{cm}^2$, R_c is 2.5 Ω, and the width of the square contact used is 200 μm. This yields transfer length L_T for n-type GaN of 2 μm. A reasonable limit for the n-type contact width is $2L_T$. Thus, the width of the n-type contact is chosen to be around $2L_T$.

Our recent study showed that the current in GaN/InGaN LEDs grown on insulating substrates crowds near the mesa edge. L_s is denoted as the *current spreading length*, that is, the length over which the current density drops to the $1/e$ value of the current density at the edge. L_s is given by

$$L_s = \sqrt{(\rho_c + \rho_p t_p) t_n / \rho_n}, \tag{2}$$

where ρ_p and ρ_n are the resistivity of the p- and n-type cladding layers, respectively, t_p and t_n are the thickness of p-type and n-type cladding layers, respectively. The spreading length for the device is around 550 μm for the device wafer,[6] which is much larger than the p-type contact width. Therefore, the current distribution can be assumed to be uniform under the p-type contact.

Another advantage of the interdigitated pattern is its scalability. High-power LEDs with large die size normally suffer from current crowding near the mesa edge when using the traditional square-shaped pattern. Due to the long light travel length, more light is reabsorbed inside the device. Using interdigitated patterns, one can solve the problem of current crowding by designing the width of the n-type contact fingers according to L_T and the width of the p-type contact fingers according to L_s. So, the light travel length toward the side of the finger can be kept as small as in small die size devices. Thus, interdigitated patterns are scalable to a certain degree.

In conclusion, the optical output power and the $I-V$ characteristics of devices with different mesa structures are studied. Devices with interdigitated patterns generally have higher efficiencies than traditional square-shaped devices. The uniform current distribution and better light extraction contribute to the efficiency increase. Due to the mesa sidewall leakage, the surface leakage current increases with the mesa perimeter. The interdigitated mesa pattern is more scalable than the traditional square-shaped structure for large die LEDs. From the design point of view, the n-type contact finger width should be limited to one or several L_T of the n-type GaN contact, and the p-type contact finger width should be limited by L_s of the LED wafer.

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